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ANALYSIS OF DECOMPRESSION TABLES CALCULATED BY NON-U.S. NAVY ME--ETC(U)

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A total of 336 depth-time combinations of air decompression tables selected from U. S. Navy and British schedules were individually analyzed by a computer using the AUTODEC system. In addition 97 schedules tested by the Experimental Diving Unit in the development of Mixed Gas Scuba tables were analyzed to compare the computer analysis with manned test data.

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ANALYSIS OF DECOMPRESSION TABLES

CALCULATED BY NON-U.S. NAVY METHODS

by
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March 31, 1980

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AUTHOR'S NOTE

It is important to recognize that the tables discussed within this report were developed between ten and twenty years ago. In light of the advances in knowledge and techniques of decompression computation, these tables are inadequate, in some areas, according to decompression safety and efficiency criteria developed by modern computer decompression programs. The knowledge and techniques applied today were not available at the time these schedules were developed. Indeed, much of the technology available today is a result of the successes and failures of the tables referred to in this report.

All schedules mentioned in this report are analyzed by knowledge available today. However, if we consider the dates of conception for these schedules, we can more fully appreciate the significant contribution to diving physiology that they represent, as a result of knowledge, skill and effort of their authors. These past efforts provided the foundations for what we can accomplish today - and hopefully may achieve tomorrow.

P. O. E.

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Peter O. Edel

ABSTRACT

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The analysis permitted evaluation of the tables as to decompression safety and relative decompression efficiency. Both British and U.S.N. schedules were found unsafe for the longer exposures, especially at the deeper depths. Recommended limits for all tables were provided for unrestricted use. In addition, extended limits were included for the U. S. Navy air tables where favorable or extremely favorable environmental and/or physiological conditions apply. The effects of those conditions in increasing or decreasing diver safety from decompression sickness were discussed, as were the principal areas of deficiency of the respective tables that contributed to violations of the tissue compartment model used in this analysis.

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ANALYSIS OF DECOMPRESSION TABLES CALCULATED BY NON-U.S. NAVY METHODS

INTRODUCTION

Although conventional mathematical approaches to pressure reduction from hyperbaric exposures adequately predict the decompression obligation in man under many conditions, present mathematical models demonstrate the inability to provide for safe ascent from the increased depths and times required for future diving programs. At the same time, many current decompression schedules, computed by methods other than those in use by the U. S. Navy, are claimed to have successful application in the field for exposure conditions more severe than present U. S. Navy operational requirements. It seems logical, therefore, to examine such methods to see if these mathematical models offer potential advantages over those in current Navy usage. By using the AUTODEC system to examine two sets of decompression schedules, computed by methods other than the ones in current use by the U. S. Navy, one may ascertain if the schedules in question appear to provide better predictions of decompression obligations than are presently available using contemporary Navy techniques.

The British Royal Navy (1) and CERIA tables (1a) were chosen for this purpose. These choices offered advantages of comparison with our present U. S. Navy Standard air diving schedules (2) with information cross-checking through data available from the Naval Diving Safety Center.

BACKGROUND

The first recorded systematic attempt to define the decompression obligation in man, utilizing scientific principles, was made by Haldane (3). He developed a formula for computing decompression tables, based upon empirical data obtained using goats exposed to pressure and later brought to the surface in stages of pressure reduction. Later evidence showed that the decompression requirements for goats, as exemplified by their no-decompression limits on HeO_2 reported by Hempleman (4), were far less than those for man determined in empirical experiments by Duffner (5). Despite this discrepancy, the Haldane tables did provide safe ascent from a number of exposure conditions using air as a breathing medium. The formula would not, however, provide adequate decompression from fairly deep depths and/or long exposures.

Recognizing that the traditional Haldane supersaturation ratio of 2 to 1 for tissue half times of 5 to 75 minutes was not sufficiently conservative for the slower tissues and too conservative for the fast tissues, Hawkins, Schilling and Hansen (6) developed tables using supersaturation ratios ranging from 1.8 to 1 for the slowest (75 min.) tissue to 5.5 to 1 for the fastest (5 min.) tissue. Yarbrough (7) later calculated and tested revised U. S. Navy tables with further modification of this concept. The same concept was also used by Van Der Aue et al (8), with the addition of a

120 minute control value for the slowest tissue half saturation time, to develop the surface decompression tables using oxygen presently in U. S. Navy use. Again, the schedules did perform for a given range of depth-time combinations but would fail beyond given limits.

To provide increased safety, the standard air decompression tables were revised by Des Granges (9) with the tissue supersaturation ratios decreasing with depth increase. This revision resulted in the standard air decompression tables presently in use by the U. S. Navy. Although still somewhat limited in scope of application, the current schedules offer significant advantages over the preceeding methods.

The present state of the art with respect to helium-oxygen decompression schedules remains far less satisfactory, however. The U. S. Navy pioneered in helium-oxygen diving over ~~the first~~ half of this century with the Momsen tables (10) which, despite some slight modifications by Molumphy (11), exist essentially in their original form. They were calculated using a modified Haldane system in which tissue half times of 5 to 70 minutes were controlled by a supersaturation ratio of 1.7 to 1. Although the above-outlined advances in concepts of decompression computations have been applied to air tables, they have not been applied to the standard He-02 schedules. A set of He-02 tables designed for SCUBA use (12) was developed using the Workman M value concept (13). However, this concept was not applied to standard tables requiring deeper and longer exposures. While the U. S. Navy saturation experience is far more satisfactory, the incidence of decompression sickness following the initial USN 1500 ft. dive indicates the need for revision of the computational method in that area as well.

The actual details of changes required in formulation to achieve the present level of competence are interesting in retrospect as an indication of a science which is far from static. These changes also illustrate the need for constant reassessment and revision to provide for the continuing increases in exposure depths and times necessary to meet expanding future requirements. The idea that new methods should be evaluated is beyond dispute. The question that remains is where to find new concepts.

During the second quarter of this century practically all new concepts and advances in deep diving originated from within the U. S. Navy, at that time the holder of a virtual monopoly in the field. Recently, however, commercial industries in this country and military and commercial organizations outside the United States have reported notable advances. Although the schedules themselves are often available in open literature, the field results are rarely reported in sufficient detail, and in some cases in sufficient honesty, to permit adequate assessment of their value. Considering the number of potential schedules available for review, the considerable expense of manned testing precludes its use as a preliminary evaluation method. From an economic standpoint, therefore, computer analysis appears the only practical method for initially evaluating such schedules.

THE AUTODEC SYSTEM

In 1975 Sea-Space Research Co. developed AUTODEC, a proprietary computer program designed for the calculation of decompression schedules. Checking this system against reliable manned test data revealed a highly satisfactory correlation between the computer prediction and previously recorded results in air and/or helium-oxygen dives ranging from no-decompression exposures to saturation. AUTODEC also successfully predicted decompression sickness in several instances prior to any manned tests of the schedules in question. For these reasons the AUTODEC method was utilized in this program to analyze the decompression tables presented.

Factors or Assumptions Used

To understand the analysis data presented, one must understand the factors and assumptions used by the system in evaluating decompression profiles. In addition to checking the pressure profile information the system will also check to see what data has been provided with respect to subject susceptibility, workload, water or chamber temperature, sleeping periods (if required), and acclimatization factor (if applicable). The factors are entered if known. If unknown, assumptions must be made regarding the data.

Some internal assumptions regarding secondary factors result of necessity from a lack of accurate and reliable data at the time the system was programmed. The factors are of minor importance in the vast majority of cases, with the assumptions made producing some slight tendency to be conservative in the computation of decompression profiles. For the purpose of analysis, this tendency can be countered to some extent by permitting small deviations from the programmed ascent control values.

The resultant analysis is valid only for the stated conditions. If, for example, one assumes a moderate workload, certainly a profile that would be adequate for that condition would be more than adequate for lesser workloads. The same profile, however, might be unsafe for higher workloads.

Subject Susceptibility

AUTODEC provides for five classifications of subject susceptibility to decompression sickness. Two of these, extreme susceptibility and extreme resistance, are not used for this study since individuals in these categories are extremely rare; consequently, the chance that one would be present in any test program is highly unlikely unless very large subject populations are used. The remaining three categories are defined as follows:

Resistant Subjects: This group includes the upper 25% of the normal diving population. Tables that would be just marginally safe for such individuals would cause decompression sickness in 75% of the subject population.

Susceptible Subjects: This category consists of the lower 25% of the normal diving population. The term, as in the case of "resistant", is used in the relative sense. Susceptible divers will suffer decompression sickness if tables that are marginally safe for the upper 75% of the subject population are followed.

Average Subjects: This group makes up the remaining 50% in the mid range between the two extremes.

In any category the worst condition is assumed. That is, the least resistant subject in any classification becomes the limiting factor. Hence, a table deemed acceptable for average subjects will be acceptable for all subjects within that group and for "resistant" subjects as well. However, a schedule which is not acceptable for average subjects but is acceptable for "resistant" subjects might well be safe for a number of subjects within the average category.

Temperature

Three levels are used in this classification:

1. Warm (or ideal): This normally applies only to dry chamber dives in which ideal temperature conditions can be maintained.

2. Normal: This would apply to waters similar to or warmer than the Gulf of Mexico near the U. S. Coast line.

3. Cold: A typical example would be North Sea water temperatures.

Workload

Five workload levels are used in this classification:

1. Severe: Maximum effort that can be sustained by a diver. An example would be lifting a 40 pound weight one and one-half feet, sixteen times within one minute.

2. Heavy: 75% of the above effort.

3. Moderate: 50% of a severe workload.

4. Light: 25% of a severe workload.

5. Rest: Normal waking activity.

Other Factors

All other factors are set to standard values, that is, no acclimatization, no sleeping cycles during the pressure exposure, etc.

METHOD

The program was divided into two phases as follows:

Phase I: Comparison of AUTODEC predictions with results of He-02 test dives reported by Workman and Reynolds (12) in an experimental series of manned exposures to develop mixed-gas SCUBA helium-oxygen decompression tables.

Phase II: Comparison of British CERIA and Royal Naval air tables with comparable U. S. Navy air decompression tables.

In each case known or assumed factors were entered into the computer via a data statement and analyzed to determine the relative safety of the schedules in question. The resultant printout provided an alpha-numeric symbol for each tissue compartment. This symbol permitted classification of each schedule into one of the following categories:

A+: Excessively conservative or safe (tissue tensions at every stage so far within acceptable values as to represent over decompression for the known, or assumed, conditions of the exposure).

A: Adequately safe (the tissue tensions within acceptable limits for the known, or assumed, conditions but not excessively so).

B: Borderline tables (tissue tensions exceed accepted values but to such a small degree that prediction is uncertain).

C: Unsafe tables (tissue tensions show significant excess beyond accepted safe values).

D: Excessively unsafe tables (tissue tensions considerably in excess of accepted safe values).

E: Hazardous tables (tissue tensions in excess of accepted safe values present a hazard to divers exposed to such profiles).

F: Excessively hazardous tables (tissue tensions elevated to provide excessive hazards to divers exposed to such profiles).

G: Tables resulting in tissue tensions beyond all above-mentioned limits.

Tables with tissue tensions of "A" or "A+" are considered safe with respect to the known, or assumed, conditions of the exposure. "B" category tables are considered borderline; decompression sickness may or may not develop. Tables in all other categories are regarded as bends-producing for the known, or assumed, conditions.

A schedule which only fails ("C" or greater classification) for "susceptible" subjects is assumed to result in 1% to 25% bends incidence. A schedule which fails for the "Average" group but is borderline or safe for "resistant" groups is assumed to result in 25% to 75% bends incidence. A table which fails for all three groups is assumed to result in 75% or greater bends incidence.

In all cases a verification of AUTODEC predictions requires a significantly large segment of the diving population. When limited groups of divers are exposed, inconsistances in a given profile may occur due to variations in subjects. A given test with only three or four subjects may not include any individuals in a "susceptible" or "resistant" category or, less likely, all subjects exposed may fall within one of these groups. Hence, when human test data is limited in terms of numbers of subjects exposed to a particular decompression profile, grouping of accumulative test results may be necessary to verify the predictions.

RESULTS

Phase I

All non-repetitive test dives included in the Workman and Reynolds report (containing 178 schedules) were analyzed by AUTODEC. Each dive was analyzed for "average" and "susceptible" subject categories. Normal water temperatures and severe workloads were assumed as indicated from the report. It was also assumed that the subjects were not acclimatized. This assumption could not realistically be substantiated from the contents of the report. Nonetheless, both the number of subjects in the program and the practical limitations of such a program with respect to the number of possible exposures to be made within a given period of time allow one to infer that no excessive degree of acclimatization existed in most cases.

Although the percentage of helium in the breathing mixtures was noted in most cases, for some tests no entries were made. In such cases the mixtures of all dives in that test series were averaged and the average helium percentage was used.

The report included test data of eight series of tests. The initial series was made to test minimal decompression dives, that is exposures in which the only decompression involved was the time required to ascend to the surface at a rate of sixty feet per minute. Five series of experiments were conducted to examine the decompression obligation wherein stage decompression was required during which the subjects breathed helium-oxygen mixtures. One series was made in which the subjects breathed oxygen during the twenty and thirty foot stages of decompression, and one test series was made involving repetitive dives. All but the last mentioned test series were analyzed by AUTODEC.

No-Decompression Exposures

Fourteen exposures were made in this series with two subjects per schedule. No symptoms of decompression sickness resulted during this test series.

The AUTODEC analysis showed all dives in this series to be safe for average or resistant subjects (A or A+). All but five exposures resulted in an AUTODEC rating of "A" or "A+" for susceptible subjects. Of these five exposures, one produced a "B" rating, two a "C" rating and two a "D" rating for the susceptible categories.

Exposures Requiring Decompression on He-02 (Series A)

The second group was comprised of five exposures using two to four subjects per exposure. Despite cases of transient pain and skin itch or rash, only two exposures resulted in clear and definite signs of decompression sickness. In both cases recompression was required.

The AUTODEC analysis showed all the exposures except one were safe for "average" or "resistant" subjects. For "susceptible" subjects three exposures were rated borderline ("B" category), one exposure had a "D" rating and another had an "E" rating.

The exposure having the worst rating by AUTODEC was one of the exposures resulting in decompression sickness in the test series.

Exposures Requiring Decompression on He-02 (Series B)

This series was comprised of six exposures utilizing four subjects per test. Apart from cutaneous manifestations, this series resulted in only one incident of decompression sickness. For average subjects the AUTODEC analysis gave an "A" or "A+" rating to all dives except one in this series. The remaining dive received a "D" rating. For susceptible subjects one of the exposures resulted in an "A" or "A+" rating, three dives had a "D" rating, and two dives had an "E" rating.

Exposures Requiring Decompression on He-02 (Series C)

This series involved twelve schedules tested with four men per pressure profile. Other than one case of skin bends and one transient symptom, the series of tests resulted in no cases of decompression sickness. For average subjects the AUTODEC analysis showed all dives to have an "A" or "A+" rating. In all but two exposures AUTODEC gave an "A" or "A+" rating to the schedules for susceptible subjects. The two remaining schedules received a "B" and "E" rating respectively.

Exposures Requiring Decompression on He-02 (Series D)

Five schedules were tested with two subjects per schedule in this series. Aside from one case involving transient or mild pain symptoms, the exposures were asymptomatic for decompression sickness. For average subjects all dives, except one with a "D" rating, had a rating of "A" or "A+". For susceptible subjects there were two dives rated "A" or "A+", two rated "D" and one dive rated "E".

Exposures Requiring Decompression on He-02 (Series E1)

Twenty-two decompression schedules were tested using two to four subjects per schedule in this series of dives. Except for cases of skin bends and transient or minor pain symptoms, this group of exposures resulted in only two cases of decompression sickness. For average subjects all dives but two had an "A" or "A+" rating. The remaining two dives received one "B" and one "D" rating respectively. For susceptible subjects the dive series received one "B", three "C", one "D", and two "E" ratings. All remaining dives had an "A" or "A+" rating.

Exposures Requiring Decompression on Oxygen (Series F)

This series involved thirty-three dives utilizing two subjects per schedule. Only one case of decompression sickness was reported. For average subjects the AUTODEC analysis showed all dives to have an "A" or "A+" rating. For susceptible subjects there were one "E", one "D", one "C" and five "B" ratings. The remainder were all either "A" or "A+" ratings. Interestingly enough, the dive with the highest rating for susceptible subjects, the "E" rated dive, was the one in which decompression sickness occurred.

Phase II

The analyses of all phase II dive schedules were made using the assumptions below:

1. The "susceptible" subject classification would be used.

2. The subjects would perform a moderate workload.

3. All dives would occur in cold water temperatures.

4. The subjects would not be acclimatized.

5. Air with a nitrogen percentage of 79.1 (balance oxygen) would serve as the breathing medium on all dives.

6. All dives would initiate and terminate from a sea-level base (pressure 1 atm. abs. or 14.696 pounds per square inch).

7. All descents would take place at the maximum rate permitted by the respective tables. In cases where the ascent involved less than 1 or 2 percent of the total bottom time, it was usually assumed that the total exposure took place at the maximum permitted depth since the ascent time becomes insignificant under such conditions.

8. All exposures would be made for the maximum depths and times permitted by the respective schedules used.

9. Decompression would take place in the exact manner prescribed by the tables in question. Oxygen when used would serve as the breathing medium for the precise times specified by the tables in question.

10. AUTODEC would be used in the "ANALYSIS" mode.

Phase IIa

Analysis of U. S. Navy Standard Air Decompression Tables

Ninety U.S.N. air decompression tables were chosen for analysis. Selection of the tables was designed to accomplish two goals:

1. Provide maximum coverage of the total depth-time combinations available.

2. Offer comparisons with other tables analyzed in connection with this project.

To allow for such comparisons with the CERIA and Royal Navy tables, some tables designated as "Exceptional Exposure Air Decompression Tables" (printed in red in the U. S. Navy Diving Manual) were included. In analysis tables and data summaries, Exceptional Exposure tables are identified by the letter "E" following the bottom time numbers. The absence of such a letter indicates tables are "Standard Air Decompression Schedules".

The results of this analysis are shown in Table I.

Phase IIb

Analysis of Blackpool Tables with Decompression on Air

Tables identified as RNPL Air Diving Tables 1968 (also referred to as CERIA tables and Blackpool tables) with decompression on air were analyzed using the same criteria applied to the analysis of the U.S.N. air tables. Eighty-nine individual depth-time combinations were analyzed. The tables to be

analyzed were selected to provide comparisons with the U. S. Navy Air Tables. When tables identified as "Extreme Duration Exposure" are reported, they are distinguished from standard tables by an "E" following the bottom time. The results of this analysis are shown in Table I.

Phase IIc

Analysis of Blackpool Tables With Decompression on Oxygen

Tables identified as RNPL Air Diving Tables 1968 (also referred to as CERIA tables and Blackpool tables) with decompression on oxygen were analyzed using the same criteria applied to the analysis of the U.S.N. air tables. Because some of the shorter depth-time combinations were not included in the oxygen decompression of these tables, only seventy-six combinations were analyzed. Aside from the use of oxygen, these tables were analyzed in the same manner as the previously-mentioned schedules. The results of this analysis are shown in Table I.

Phase IId

Analysis of the Royal Naval Air Decompression Tables

Eighty-one RN tables were analyzed in the same manner as the previously-mentioned tables. A slight problem in making comparisons with other tables occurred since the Royal Navy Tables were designed for the metric system. In making comparisons it must be remembered that the RN schedules are slightly shallower than the other schedules presented on the comparison tables. Table I indicates results of this analysis.

TABLE I

DEPTH	EXPOSURE TIME (MINUTES)				ANALYSIS RATING			
Feet/Meters*	USN	Blackpool Air	Blackpool 02	RN	USN	Blackpool Air	Blackpool 02	RN
30/	7200	7200	7200	--	E	E	E	--
40/12	180	180	180	195	A	A	A+	A
40/12	250	240	240	255	A	A	A+	A
40/12	480E	420	420	390	B	A	A	A
40/12	720E	720E	720E	660	D	D	C	D
50/15	90	90	---	85	A	A	-	A
50/15	120	120	120	120	A	A	A+	A
50/15	180	180	180	190	A	A	A+	A

DEPTH	EXPOSURE TIME (MINUTES)				ANALYSIS RATING			
Feet/Meters*	USN	Blackpool Air	Blackpool 02	RN	USN	Blackpool Air	Blackpool 02	RN
50/15	240	240	240	240E	A	A	A	A
60/18	60	60	---	60	A	A	-	A
60/18	80	80	80	90	A	A	A+	A
60/18	120	120	120	120	A	A	A+	A
60/18	180	180	180	180E	A	A	A+	A
60/18	240E	240	240	255E	A	A	A+	A
70/21	50	50	55	55	A	A	A+	A
70/21	80	80	80	85	A	A	A+	A
70/21	120	120	120	120E	A	A	A	A
70/21	170	180	180	180E	A	A	A	A
80/24	40	40	45	40	A	A	A+	A
80/24	80	80	80	80E	A	A	A+	A
80/24	120	120	120	120E	A	A	A	A
80/24	180E	180	180	160E	A	B	A	A
80/24	240E	240	240	---	D	E	D	-
80/24	720E	660E	660E	---	G	G	G	-
90/27	30	30	---	30	A	A	-	A
90/27	40	40	40	40	A	A	A+	A
90/27	60	60	60	60	A	A	A+	A
90/27	80	80	80	80E	A	A	A	A
90/27	100	105	105	100E	A	B	A	A
90/27	120	120	120	120E	B	B	A	A
100/30	25	25	---	25	A	A	-	A+
100/30	40	40	40	40	A	A+	A+	A+
100/30	60	60	60	60E	A	A	A	A
100/30	90	90	90	90E	E	B	A	A
100/30	120	120	120	120E	D	B	A	A
100/30	180E	180	180	---	E	E	C	-
120/36	15	15	---	14	A	A+	-	A+
120/36	30	30	30	30	A	A	A+	A
120/36	60	60	60	60E	E	C	A	A
120/36	90	90	90	90E	E	D	B	A
120/36	120E	120	120	120E	F	D	C	B
120/36	180E	180	180	---	E	F	E	-
140/42	10	10	---	9	A	A	-	A+
140/42	15	15	---	15	A	A+	-	A
140/42	20	20	---	20	A	A	-	A
140/42	25	25	25	25	A	A	A+	A
140/42	30	30	30	30	A	A	A+	A
140/42	40	40	40	40E	D	A	A	A
140/42	50	50	50	50E	D	D	B	B
140/42	60	60	60	60E	E	E	A	C
140/42	90E	90	90	95E	F	E	E	C
140/42	120E	120	120	115E	F	E	C	E
140/42	180E	165	165	---	F	F	F	-
160/48	10	10	---	10	A	A+	-	A+
160/48	15	15	---	15	A	A	-	A+
160/48	20	20	20	20	A	A	A+	A

DEPTH	EXPOSURE TIME (MINUTES)				ANALYSIS RATING			
Feet/Meters*	USN	Blackpool Air	Blackpool 02	RN	USN	Blackpool Air	Blackpool 02	RN
160/48	25	25	25	25	A	A	A+	A
160/48	30	30	30	30E	D	A	A	A
160/48	40	40	40	40E	D	D	A	C
160/48	50	50	50	50E	F	E	B	B
160/48	60	60	60	60E	F	E	E	B
160/48	70E	75	75	70E	F	F	F	B
180/54	10	10	10	10	A	A	A+	A+
180/54	20	20	20	20	A	A	A+	A
180/54	30	30	30	30E	C	D	A	A
180/54	40	40	40	40E	E	E	A	A
180/54	50	50	50	50E	F	F	E	C
180/54	60	60	60	60E	G	F	F	B
200/60	10E	10	10	10	A	A	A+	A+
200/60	20E	20	20	20E	A	A	A	A
200/60	30E	30	30	30E	E	E	A	A
200/60	40E	40	40	40E	F	F	E	A
200/60	50E	50	50	50E	F	F	F	A
200/60	60E	60	60	60E	G	F	F	B
200/60	90E	80	80	---	G	F	F	-
220/66	10E	10	---	12	A	A	-	A+
220/66	15E	15	15	16	A	A	A	A
220/66	20E	20	20	20	A	A	A	A
220/66	30E	30	30	30	E	F	E	A
220/66	40E	40	40	40E	F	F	E	A
220/66	50E	50	50	---	F	F	F	-
220/66	---	120E	120E	---	-	G	F	-
240/72	10E	10	---	12	A	A	-	A+
240/72	15E	15	15	16	A	A	A	A
240/72	20E	20	20	20	E	E	B	A
240/72	25E	25	25	25	G	E	E	A
240/72	30E	30	30	30E	F	F	F	A
240/72	40E	40	40	35E	G	G	G	A
240/72	50E	60	60	---	G	G	F	-
250/75	10E	10	10	12	A	A	A	A+
250/75	15E	15	15	16	B	C	A	A

*meters apply only to RN table.

DISCUSSION

Phase I

Phase I illustrated the ability of AUTODEC to provide an accurate prediction of decompression sickness incidence. Providing schedules could be grouped, accurate AUTODEC predictions resulted even when they utilized data derived

from small numbers of test subjects with unknown susceptibility to decompression sickness. Adjustments, however, were necessary. Only twenty-nine subjects participated in the test program reported by Workman and Reynolds (12). Such a small subject population would be unlikely to include any individual representing the lower limit of the "susceptible" category used by AUTODEC. In view of this improbability, the evaluation of the susceptible group designation was adjusted, to conform with the limited subject population used, by adjusting the limits upward. This alteration involved a downwards adjustment of two letter groups. Hence, an analysis which resulted in an "A", "B", or "C" group (for susceptible subjects only) was deemed acceptable, a "D" group considered borderline, and an "E" group regarded as failure. No adjustment was made for the "Average" classification, nor would any be necessary unless extremely small test subject populations were involved. Although this limited adjustment presented a satisfactory solution for the subject population as a whole, one must remember only two or four subjects participated in each test of the series. It is unlikely, therefore, that one susceptible subject participated in each of the tests. For that matter, no assurance exists that some dives involved one or more test subjects in the "average" classification. Furthermore, since the criteria used for the "average" classification are based upon the least resistant member of that category, it seems improbable such a hypothetical individual participated in all dives. Therefore, an analysis of any specific dive would not necessarily be expected to correlate with the test data supplied.

This qualification, however, applies only on a dive-to-dive basis. Over the whole series such inequities should cancel out and provide an overall subject response representative of the subject population used. The dives, therefore, were grouped into their respective test groups to provide a total bends incidence for the series as a whole with respect to the manned test data. Likewise, the analysis predictions made on an individual dive basis were totaled for the entire dive series. These totals were then compared to see how close a correlation existed between the manned test data and the AUTODEC predictions.

In the No-Decompression manned dives, no cases of decompression sickness occurred over the entire test series. AUTODEC predicted a zero bends incidence for that group of exposures.

In the series-A exposures, two cases of decompression sickness occurred in manned testing. AUTODEC predicted one case would occur for the average and one for susceptible classifications.

The series-B exposures resulted in one case of decompression sickness during the manned test series. AUTODEC predicted a single case of decompression sickness would occur.

Two cases of decompression sickness occurred during the testing of the series-C exposures. AUTODEC predicted two cases of decompression sickness using the average subject classification and one using the susceptible subject classification.

The series-D dives were asymptomatic aside from one case involving mild or transient pain symptoms. AUTODEC predicted one case of decompression sickness.

In the series-E1 exposures two cases of decompression sickness occurred. AUTODEC predicted one case using the average subject classification and two using the susceptible subject classification.

One case of decompression sickness resulted from the series-F manned tests. AUTODEC predicted one case for susceptible subjects and none for average subjects.

The results are summarized in Table #2.

TABLE II

Dive Series	# Schedules	# Subjects	AUTODEC Predictions Avg. Sub.	AUTODEC Predictions Sus. Sub.	No. Bends
No-Decompression	14	28	0	0	0
Series-A	5	18	1	1	2
Series-B	6	24	2	1	1
Series-C	12	48	0	1	0
Series-D	5	10	1	1	0
Series-E1	22	84	1	2	2
Series-F	33	66	0	1	1
TOTAL	97	278	5	7	6

Clearly, the test series as a whole reveals a strong correlation between the AUTODEC predictions and the observed results regarding decompression sickness.

The limited number of subjects applied to any given schedule and the lack of information regarding subject susceptibility together precluded accurate predictions on a dive-to-dive basis; nevertheless, interestingly in series-A the dive AUTODEC predicted as the worst of the series (a 180 FSW exposure for 30 minutes), was indeed one of the two schedules resulting in decompression sickness. Also, the only table in the series-F group to result in decompression sickness was likewise the only one AUTODEC predicted unsafe. These results suggest that, with larger subject populations utilized for each depth-time combination, AUTODEC could be realistically applied to predictions on an individual table basis.

Note the predictions for Phase I were provided for the specific conditions under which the tests were conducted and, as such, provide no definite indication of the performance of such tables under open water conditions. When the schedules are applied operationally, in general, the following three factors that would affect the bends incidence must be considered:

1. When applied to a larger segment of the subject population, some individuals with greater susceptibility than those used during the experimental series will probably utilize the tables. All other conditions being equal, such individuals would have symptoms of decompression sickness using schedules safe for the test subject population.

2. All other conditions being equal, application of these schedules in cold water would increase the incidence of decompression sickness in many of the schedules.

3. All other conditions being equal, any reduction of workload, which in this series approached a maximum level, would result in reduced incidence of decompression sickness.

An additional safety factor arises in operational use. Although in an experimental test series the dives are normally conducted to the limiting depths and times prescribed by the tables, in practice, only infrequently is either limit reached, and very rarely is a normal dive made to the combined depth-time limitations. Hence, all else being equal, this factor should reduce the anticipated decompression sickness in operational use.

Phase II

Based upon analysis criteria described, AUTODEC labeled 17 out of 55 U. S. Navy Standard Air decompression tables unsafe. The failure rate for these tables was 31%. If the exceptional exposure tables are included, the failure rate increases to 47%. The Exceptional Exposure tables selected showed a failure rate of over 70%.

This percentage should not necessarily be applied to the tables as a whole. The selection method was designed to provide for a comparison with other schedules; consequently, some inequities could arise from attempts to apply these figures to the U. S. Navy tables in order to determine the percentage of tables safely utilizable for the specific conditions of the analysis. With respect to the Exceptional Exposure tables, one should note no analysis was made on schedules deeper than 250 feet.

The analysis does provide an identification of the safe limits, for the previously stated conditions, to which these tables may be applied. Graph #1 illustrates these limits. Notice the safe limits impose a restriction of 60 minutes bottom time at 100 FSW and 30 minutes or less for 120 feet and deeper dives.

Although the criteria used in this analysis are designed to provide for reasonably adverse conditions, more limiting conditions may occasionally occur. For example, all other conditions remaining the same, any extreme exertion, diving in unusually frigid waters, or the use of very susceptible divers (estimated to be less than 1% of the normal diving population) could increase the decompression requirements.

Realistically, however, most dives will be made under more favorable conditions: subjects with greater resistance to decompression sickness, warmer water temperatures, acclimatized subjects, lesser workloads, and/or dives made for shorter bottom times and/or to shallower depths than provided for by the schedules used. Any of these factors would tend to decrease the decompression obligation for the exposure.

Although a computer assessment of the schedules for favorable conditions was beyond the scope of this investigation, decompression sickness data from the Naval Safety Center in Norfolk, Virginia, was reviewed to provide an indication of table performance under ideal or favorable conditions. To eliminate any reasonable question of reporting accuracy, unusual conditions, unusually susceptible subjects, possible incorrect diagnosis, etc., only dives involving several subjects to a given depth and exposure time, and/or dives made under controlled conditions, were selected. Two groups of exposures appeared to satisfy the above requirements:

1. Four cases of decompression sickness following open water dives at 125 FSW for 58 to 66 minutes with decompression on a 130/70 schedule.

2. Five cases following dry chamber dives, with subjects at rest, at depths of 185 to 188 FSW for exposure times of 45 minutes (plus or minus one minute) with decompression on a 190/50 air decompression schedule.

Case #1 is interesting because the divers had been making several dives (between 3 and 13 dives) within the previous 10 day interval. This frequency would suggest that at least 3 of the divers (with seven or more dives during the above-mentioned time period) were to some degree acclimatized and hence would be expected to have increased resistance to decompression sickness. In addition, the depth and exposure times were significantly less than those permitted by the table used. The only adverse factor reported was the workload, which was considered heavy. In spite of such favorable conditions, decompression sickness occurred following the above-mentioned exposures.

Case #2 likewise involved exposures significantly less than the limits of the decompression table used. In these cases no subject made more than one dive within the previous 10 day period, and hence none could be considered acclimatized. However, no workload was required during this exposure, and the divers could therefore be considered at rest. The temperature level in the test chamber could be considered ideal. In spite of these favorable factors, decompression sickness occurred in five subjects.

Interestingly, in both cases decompression sickness occurred at twice the exposure times AUTODEC predicted safe for adverse conditions. Seemingly, therefore, doubling the AUTODEC predicted limit appears to be the maximum exposure time reasonably permissible under the most favorable conditions in resting dives with acclimatized divers and normal water temperatures with depths and exposure times significantly less than the limits for which the table was designed, and with divers known, (or believed to be) more resistant to decompression sickness than the average individual. Needless-to-say, such conditions would not often occur in practice.

Based upon this study it appears possible to suggest the following three zones of operations for the standard air diving tables:

GREEN: No restriction within recommended AUTODEC predicted limits.

YELLOW: Dives to within 1.5 times AUTODEC limits under generally favorable conditions.

RED: Dives under extremely favorable conditions to twice the AUTODEC predicted safe limits.

The suggested limits for these groups are shown in Table III.

TABLE III

Recommended Limits for U.S.N. Std. Air Tables

Depth*	Exposure Time Limits (min.)		
(FSW)	Green	Yellow	Red
40	300		
50	240		
60	200		
70	170		
80	150		
90	100		
100	60	90	120**
110	40	60	80
120	30	45	60
140	30	45	60
160	25	35	50
180	20	30	40
190	20	30	40

*Data is available only for the depth range given. Insufficient data is available to indicate assurance of reasonable safety beyond this area. In addition, shallower depths offer sufficient time within the green zone to make further extensions unnecessary.

**Represents dive on Exceptional Exposure table.

Note: Dives are not recommended beyond the Green limits. It is recognized, however, that some exceptional circumstances could require exposures beyond normally safe limits. Under such circumstances such exposures should be relatively safe providing one adheres to the conditions for the Yellow and Red limits.

GREEN Dives: No restrictions (possible decompression sickness in very susceptible subjects).

YELLOW Dives: Exposures are permitted if bottom times are at least 2 minutes less and depths at least 2 feet less than tables permit, if heavy workloads (equivalent to moderate workloads in AUTODEC classification) are not required, and if very cold water temperatures are not involved. Divers who have shown a tendency to be relatively susceptible to decompression sickness should not make dives in this group unless they have had a sufficient number

of dives in the green zone within the previous five days to indicate some degree of acclimatization.

RED Dives: Exposures in which bottom times are at least 5 minutes less and depths are at least 5 feet less than the tables permit. Divers must be at rest or performing very light workloads. Not applicable for cold water temperatures. Divers should be relatively resistant to decompression sickness or be of average resistance with sufficient dives in the Green and Yellow zones over the previous 5 days to indicate some degree of acclimatization. Not permitted under any circumstances for divers known, or believed to be, relatively susceptible.

Note that evaluation was made solely for individual dives. The evaluation is not intended to be applied to repetitive dive situations.

While the above table may extend the scope of application of the U. S. Navy tables under some circumstances to meet some operational requirements, the restrictions upon the extensions make this table a temporary solution at best. The limitations of unrestricted diving (Green zone) below 100 feet are sufficiently restraining as to suggest a definite need for future additional tables that can offer a permanent solution to the problem. Using the U. S. Navy tables as reference, the other tables were compared for maximum safe operational limits.

As Table #1 indicates, the Blackpool tables, using air decompression, provided some increase in safe exposure time. In part, this increase was due to the use of deeper initial decompression stops. Many U. S. Navy schedules analyzed failed because of inadequate decompression times at the deeper levels. However, in the Blackpool tables, with decompression on air, the advantages of the deeper stops were to some extent countered by the short time spent at those levels with, in many cases, ascent to a second decompression stop 20 to 40 feet shallower than the initial one. Hence, similar violations of the mathematical model occurred. The major differences for Blackpool tables, as compared with U. S. Navy schedules were:

1. The violations usually appeared at a slightly shallower depth.

2. Slightly slower tissue compartments were involved (suggesting a slightly reduced percentage of type II decompression sickness symptoms).

Both tables show inadequacies regarding management of the slower tissue half-time compartments. These present problems in the longer and/or deeper schedules. In the Blackpool #1 tables the requirement to surface from a final decompression stop of 20 FSW (as opposed to 10 FSW in the U.S.N. air schedules) complicates the problem by creating a much lower outward partial pressure gradient (inert gas partial pressure in the bodily tissues/inspired inert gas partial pressure). As a result, much more time is required to decompress from a final decompression stop of 20 feet than from a 10 foot final stop. The additional time and complication required are, however, more than compensated for by the elimination of the 10 ft. decompression level when severe sea states would make decompression at 10 feet unfeasible and the lack of a chamber would make surface decompression impossible.

A glance at Graph #1 shows the difference between the Blackpool #1 table and the U. S. Navy air schedules to be more academic than practical. The increases in exposure time for depth are too small to provide any meaningful difference in performance.

As Graph #1 demonstrates, the Blackpool #2 table (using oxygen during decompression) does show a significant advantage over the previous two tables discussed. This advantage is interesting since the use of oxygen appears to be basically a modification of the Blackpool #1 with an apparently over-conservative approach to the use of oxygen during decompression. This appears to be substantiated by the decrease in safety at the deeper levels, where the ratio of oxygen breathing time/air breathing time decreases during decompression. Although the approach is successful in increasing the safe exposure time, it also results in somewhat overconservative decompression schedules for the shorter bottom times as the "A+" ratings in Table #1 indicate.

The placement of oxygen during decompression is interesting in the Blackpool table. When intermittent air-oxygen mixtures are used during decompression, the normal sequence is air during the first portion of a decompression stop (after arriving at the new depth level), followed by oxygen. The Blackpool table reverses this procedure. Decompression mathematics suggest that the usual sequence produces greater efficiency with respect to inert gas elimination.

For example, assume that the diver arrives at the 20 foot level with 80 FSW in his 80 minute half-time tissue, which is at that time controlling or limiting decompression. Also assume one wishes to reduce this level to 54 FSW prior to leaving this level for surface. If 80 minutes are to be spent in either sequence breathing air, with the balance of the time spent breathing oxygen, one can calculate the total time required in both cases to reduce the tissue tension level to the desired value.

Using the method described by Workman (13) and assuming 80% efficiency for oxygen, one can calculate that with a nitrogen partial pressure of 53 X .791 = 41.923 (at 20 FSW 53 FSW = absolute depth, 79.1% = the percentage of nitrogen in air) the inert gas lost by the standard method would be 19.0385 FSW during the initial air breathing period, leaving 61 FSW remaining, which would be further reduced to the required level after 20 minutes of oxygen breathing. If oxygen were breathed initially after arrival at a decompression stop, 30 minutes would be required to reduce the inert gas level to the point at which an additional 80 minutes spent breathing air could eliminate sufficient gas to permit an ascent to surface pressure. Thus, in this example, a 10% time increase would be required by the oxygen-air sequence as compared with the air-oxygen sequence. This percentage would decrease for faster tissue half-times, but by the same token would increase as longer and longer tissue half-times are involved.

The vaso-constrictive effect of oxygen underlies another argument in favor of sequencing air prior to oxygen. It is generally accepted that most decompression profiles involve some bubble formation. Logically, one assumes most bubbles form upon the diver's arrival, or shortly after his arrival, at the decompression stop following pressure reduction. In successful profiles the bubbles formed do not attain a critical size and are probably

rapidly dissolved within the tissues. Bubbles in the vascular system probably do little, if any, harm unless trapped in the capillary beds, where subsequent blockage to perfusion and bubble growth from available supplies of inert gas combine to produce symptoms of decompression sickness. It seems disadvantageous, therefore, to apply oxygen (thereby constricting the blood vessels) upon arrival at a new pressure level, when bubble formation should be the greatest.

Although the use of Blackpool table #2 produces a significant increase in safe bottom times, the increase is somewhat less than desired below 100 feet. In addition, the use of oxygen precludes the application of this table to many situations where oxygen is either unavailable or represents an undesirable complication.

Below 200 FSW, the Royal Navy schedules, with decompression totally on air, performed as well or better than the Blackpool #2 tables in providing maximum safe bottom times. Below 200 feet, the Royal Naval tables provided significantly more safe bottom time than any other table, as Table #4 reveals:

TABLE IV

Comparison of Maximum Safe Exposure Times

Depth	Maximum Safe Exposure Times (minutes)			
Ft./meters*	U.S.N.	Blackpool #1	Blackpool #2	RN
40/12	250	420	420	390
50/15	240	240	240	240
60/18	240	240	240	255
70/21	170	180	180	180
80/24	180	180	180	160
90/27	100	80	120	120
100/30	60	60	120	120
120/36	30	30	60	90
140/42	30	40	40	40
160/48	25	30	40	30
180/54	20	20	40	40
200/60	20	20	30	50
220/66	20	20	20	40
240/72	15	15	15	35

*Meters apply only to RN table.

Note: Below 200 feet times RN Max. safe bottom times apply to "Deep Air Table" (table 11). All other times apply to standard air tables (table 12).

Up to this point, nothing has been said regarding decompression efficiency. Obviously, a safe schedule can be made for any exposure, providing sufficient time is allowed for decompression. If this time becomes excessive, the value

of the schedule diminishes or vanishes entirely. Practical operation cannot afford to allow for multi-hour decompression following a 60 minute dive to 100 feet, regardless of the degree of safety offered. Decompression efficiency is the ability of a schedule to provide safety from decompression sickness within the shortest possible time spent in decompression.

"Decompression safety" may be defined as the degree of safety which results from use of the schedules as measured by the incidence of decompression sickness. Due to the large variations in human response to decompression profiles, a table which results in 0% incidence of decompression sickness is not realistically achievable. However, a decompression sickness incidence of 1% or less is attainable and such tables would be considered in this analysis as "safe".

Such a definition would include any table which achieved this result regardless of the decompression time involved. An optimum table might be considered as one which resulted in a 1% (or less) bends incidence within the minimum possible decompression time. Such a table would be considered to be both "safe" and "efficient" with respect to providing for the decompression obligations of the exposures in question.

"Decompression efficiency" is therefore the measure of the adequacy of the decompression profile with respect to the actual time required to produce the required level of safety. Hence, a table which provides a decompression incidence of 1% or less within the minimum possible decompression time would be considered to have a "decompression efficiency" rating of 100%. If on the other hand the table resulted in twice the time actually required to achieve this purpose the "decompression efficiency" rating would only be considered to be 50% and such a table, although safe, could not be considered to be efficient. Further, it can be argued that a significant time beyond that actually required to provide safe decompression exposes the diver unnecessarily to the natural hazards of the water environment and hence places him at risk. Therefore extensions of time, beyond the actual decompression requirements, could be considered to produce an unsafe condition by virtue of a prolonged (or unnecessary) exposure to a hostile environment.

Using the U.S.N. maximum safety bottom times, Table #5 compares the decompression times for all tables.

TABLE V

Comparison of Decompression Times for Maximum Safe USN Exposure Time

Depth	TOB	--------Decompression Times (minutes)----			
Ft./meters*	(min.)	U.S.N.	Blackpool #1	Blackpool #2	RN
40/12	250	12	47	25	20
50/15	240	47	97	52	50
60/18	240	82	137	87	90

Depth	TOB	--------Decompression Times (minutes)----			
Ft./meters*	(min.)	U.S.N.	Blackpool #1	Blackpool #2	RN
70/21	170	100	162	112	60
80/24	180	122	187	132	130+
90/27	100	77	167	117	80
100/30	60	39	122	72	45
120/36	30	16	47	27	20
140/42	30	29	77	42	30
160/48	25	30	77	47	35
180/54	20	26	62	37	30
200/60	20	40	82	47	40
220/66	20	43	107	57	80
240/72	15	35	67	37	74
250/75	15	39	77	42	77
TOTAL DEC. TIMES		737	1435	933	861

*Meters apply only to RN table.

Note: Below 200 feet times RN Max. safe bottom times apply to "Deep Air Table" (table 11). All other times apply to standard air tables (table 12).

Notice that the exposure times are safe for all schedules presented in table V. Additional time does not confer additional safety, except possibly for extremely susceptible individuals not covered by this analysis. Yet interestingly while both the U. S. Navy and the Blackpool #1 tables had approximately equal limitations with respect to maximum safe exposure times, the Blackpool #1 table required an average of twice as much decompression time as the U. S. N. schedules. Indeed, even the oxygen modification for the Blackpool schedules requires more time than for the Navy schedules. The closest approximation of U. S. Navy decompression times can be found using the Royal Navy tables. But even here the U. S. Navy tables are more efficient, decompressing the diver in about 85% of the time required by the Royal Navy tables. Although very limited in terms of maximum safe exposure times, the U. S. Navy tables within their safe operating range are more efficient than any other table analyzed in this study.

A question arises as to why the RN tables, with decompression times only slightly greater than the U. S. N. schedules, can offer much greater safe exposure times, compared to the Blackpool #1 tables with an average of double the decompression times required by the U. S. Navy. The answer lies in the complexity of decompression calculations for multi-staged ascent profiles. If a decompression table requires an initial ascent to 40 feet, there are five stages, including the ascent to surface pressure, which must meet the decompression obligation in man for the required conditions. Generally tables

may be extremely conservative (involving over-decompression) in all but one or two stages. In adequate tables these one or two stages may be just within the safe criteria for providing adequate decompression. The other stages, however, may inflate the overall time to double (as is the case for the Blackpool #1 schedule), or even more, of the total time required. In tables failing to provide adequate decompression, this additional time is of no benefit if even one single stage involves one tissue half-time compartment violation. Hence, total decompression time is of little or no value as an indication of decompression adequacy.

Incidentally, as analyzed by the AUTODEC method, all tables suffered to some extent from variations during decompression, from falling just within (or exceeding) decompression requirements during a portion of the profile while exhibiting some degree of over-decompression on other portions.

While application of any table, or combining the best features of any group of tables analyzed to date may offer some degree of improvement, a more efficient and permanent solution only lies in application of decompression criteria more accurately representing the decompression obligation in man.

CONCLUSIONS

1. That the U. S. Navy, Royal Navy, and Blackpool air tables are unsafe for the longer exposure times.

2. That none of the tables analyzed offers optimum efficiency in decompression procedures.

RECOMMENDATIONS

1. That exposures using the U. S. Navy Standard Air Decompression Tables be limited to bottom times identified in this report as being within the "Green Dive" area.

2. That the U. S. Navy Air Decompression Tables be replaced by tables utilizing contemporary methods of decompression computation at the earliest opportunity.

3. That, as an interim measure, and when required by exceptional circumstances, dives may be made within the areas identified within this report as "yellow" and "red" when the conditions specified for such dives permit.

4. That no dives be made using exposures beyond those identified in the "red" area.

5. That further analysis be made of other Navy and non-Navy decompression tables.

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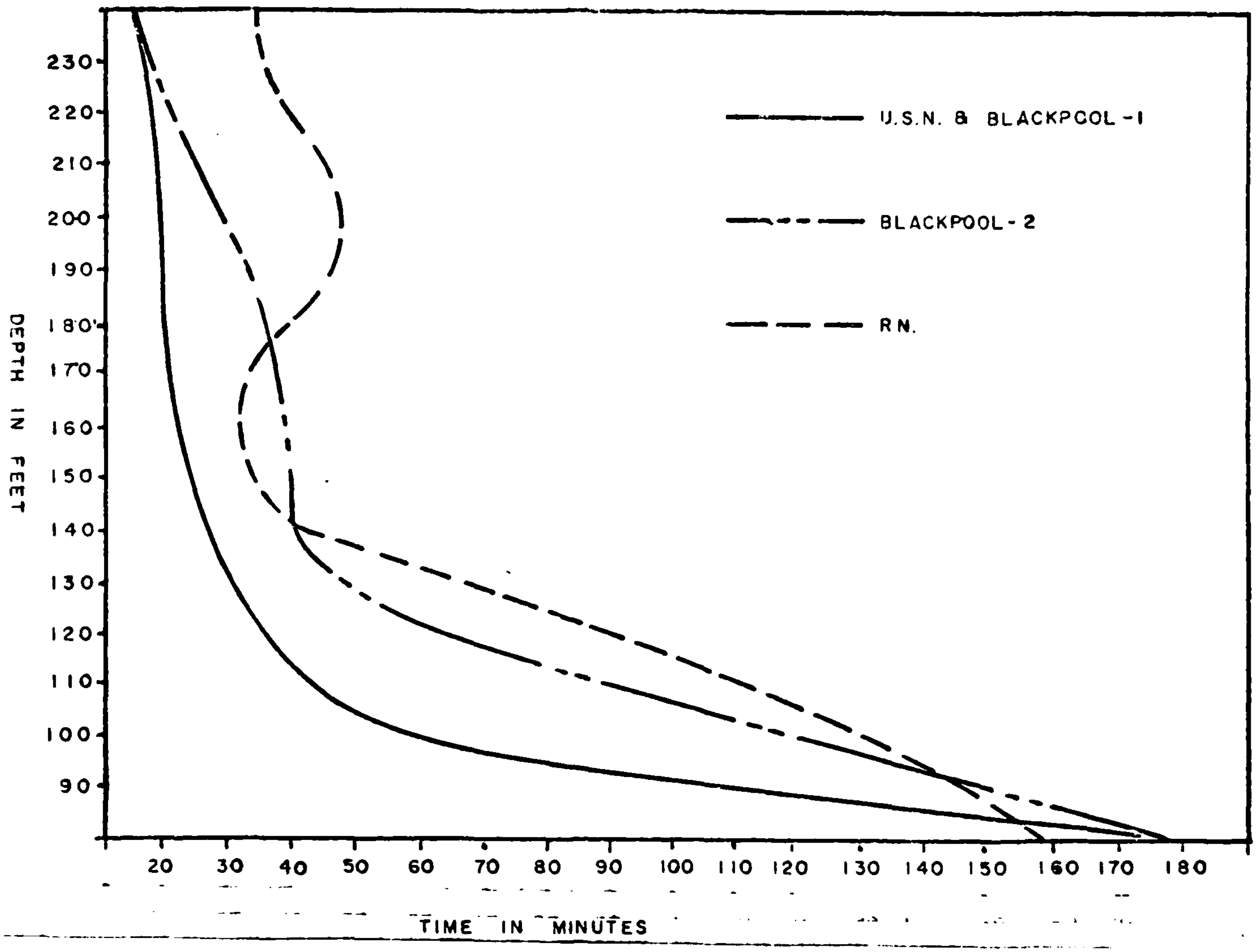

Fig. #1 - Comparison of Safe Bottom Time for UK & USN Air Tables